LA-UR-21-28063
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Title: Sensitivity of FDTD modeling of VLF Signals to D-Region Chemistry: Quiescent & Disturbed Conditions

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Intended for: ICEAA 2021, 2021-08-09/2021-08-13 (Honolulu, Hawaii, United States)

Issued: 2021-08-11

Sensitivity of FDTD modeling of VLF Signals to D-Region Chemistry: Quiescent & Disturbed Conditions

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August 13, 2021

Motivation & Overview

1. Radio signals are strongly impacted by natural and artificial ionospheric disturbances which can be challenging to model.
2. This is especially true of D-Region chemistry which is affected from below by shocks, acoustic-gravity waves and thunderstorm electric fields, and from above by solar x-rays, high-energy protons, and precipitating electrons.
3. Detailed chemistry schemes exist with many 10s of species and many 100s of reactions, that have been used to calculate RF absorption during geomagnetic events.
4. In contrast, advanced studies of VLF signal propagation typically employ reduced D-Region chemistry schemes that rely upon simplified parameterizations of electron attachment, detachment and recombination.
5. LANL is developing a suite of tools to study D-Region impacts on RF signals, and explore sensitivity to D-Region chemistry schemes.
6. This will talk will focus on GeoRad-MicroFade, a frequency-domain fullwave solver.
7. Implementation into a FDTD solver is ongoing.

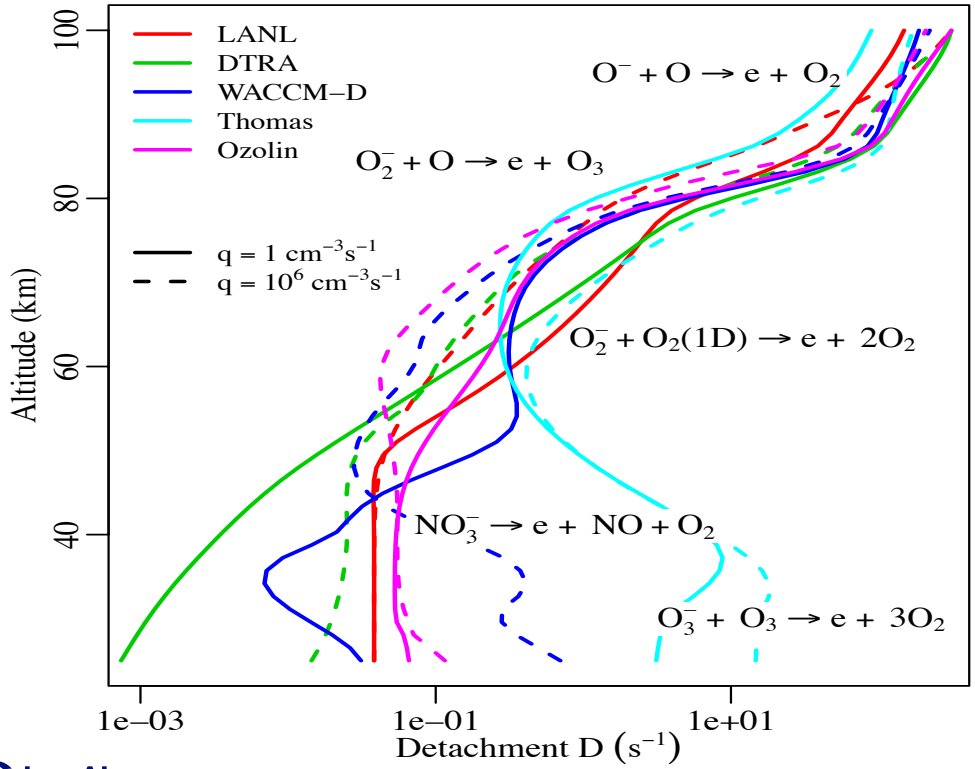
LANL GeoRad Tool Suite

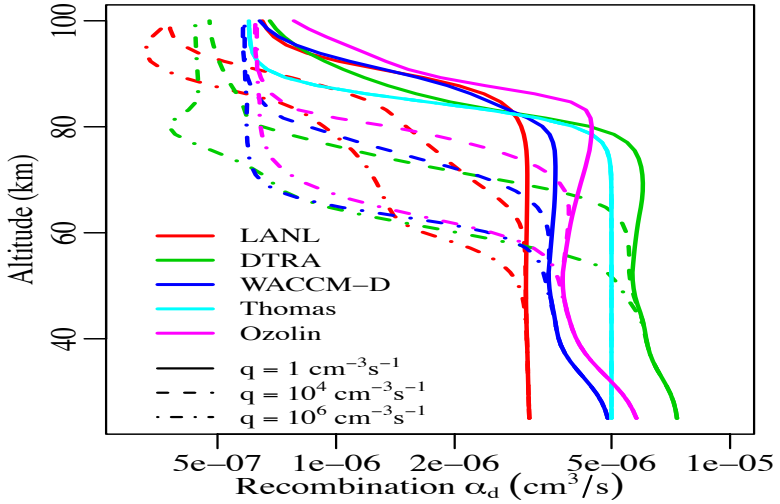
- LANL is developing the GeoRad Tool Suite to study the impact of ionospheric disturbance on communications:
  - GeoRad-ChemLab: a unique modeling environment to compare advanced chemistry schemes.
  - GeoRad-Ionosphere: a global ionosphere model, based on NRL's SAMI3 model, with an emerging variable resolution (nested-grid) capability.
  - GeoRad-FDTD: a full wave Finite-Difference Time-Domain (FDTD) model built on top of a unstructured Voronoi tessellation.
  - GeoRad-MicroFade: a full wave Frequency-Domain solver with extremely accurate numerics and chemistry inputs.

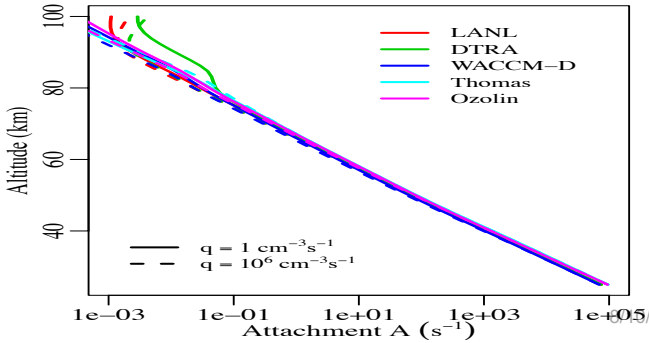
Comparing Advanced D-Region Chemistry Schemes

- GeoRad-ChemLab is 1D vertically-resolved framework to compare different chemistry schemes, typically many 10s of species and 100s of reactions.
- Complexity can be understood in terms of
  1. Net Attachment of electrons to neutrals (A).
  2. Net Detachment of electrons from negative ions (D).
  3. Net Recombination of electrons with positive ions (α_d).
  4. Net Recombination of electrons with negative ions (α_i).
- These four functions depend on forcing, e.g. UV radiation, solar protons, etc.
  1. Time-dependent source of ionization (q), units of $1/cm^3/s$.
- Forcing, q, also effects neutral balance (NO, NO_2, O_3, etc.).
- We are exploring altitude- and q-dependence of these four parameters to develop a new simplified scheme.

Altitude Dependence of (A,D,α_d,α_i)

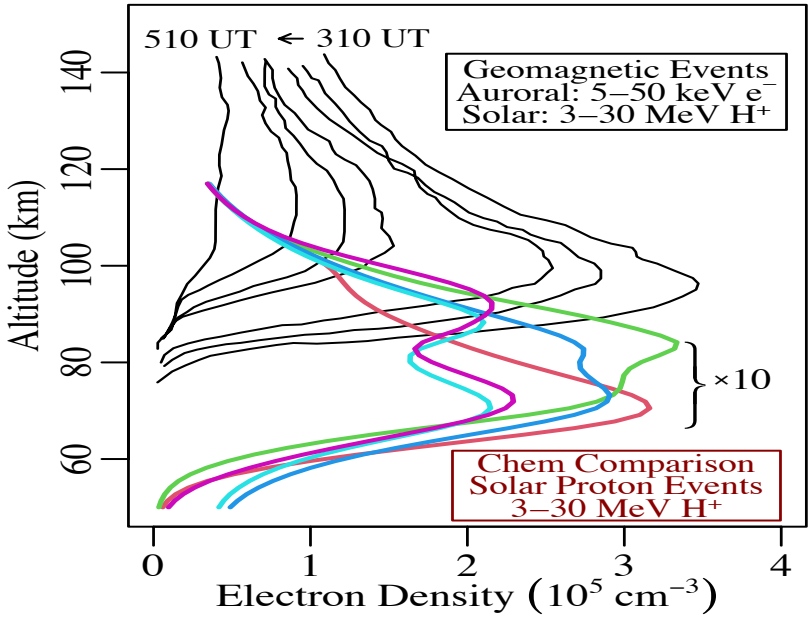


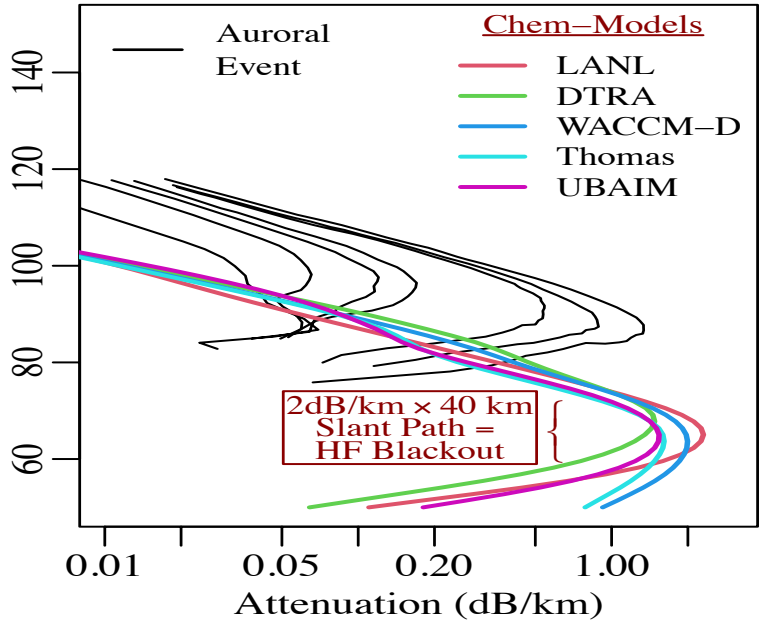




Why D-Region Chem is Important for Comms Impacts

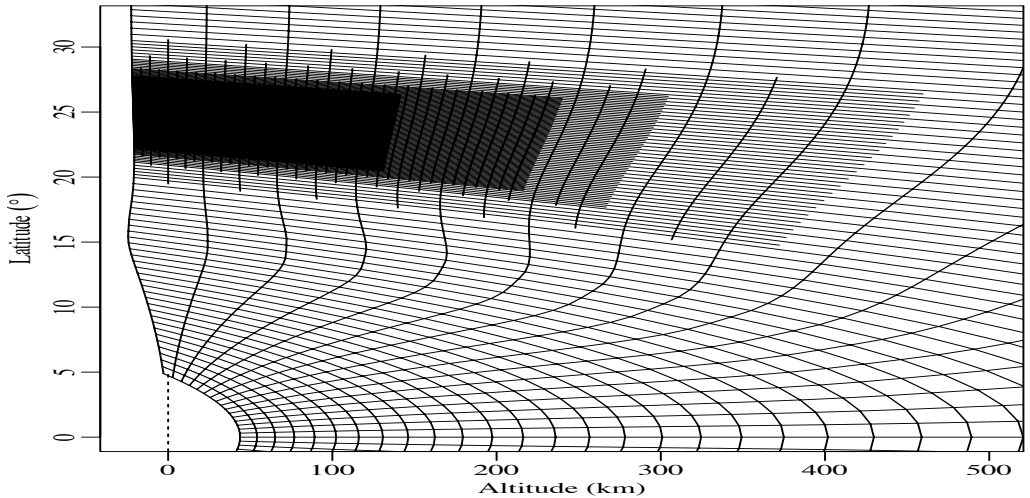
- MeV protons from solar flares cause HF blackouts over wide regions poleward of 65 N/S, grounding aircraft. Impact larger then keV auroral electrons.





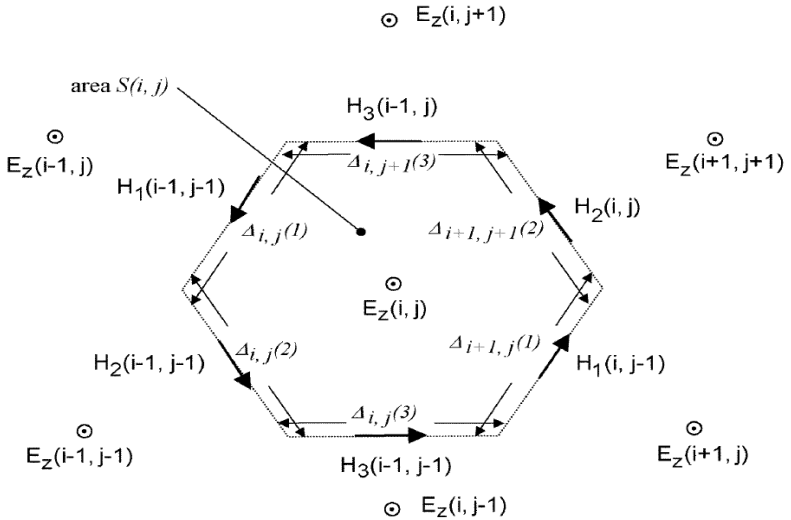
Ongoing Work: How do we Incorporate & Resolve this complexity in a global ionosphere model?

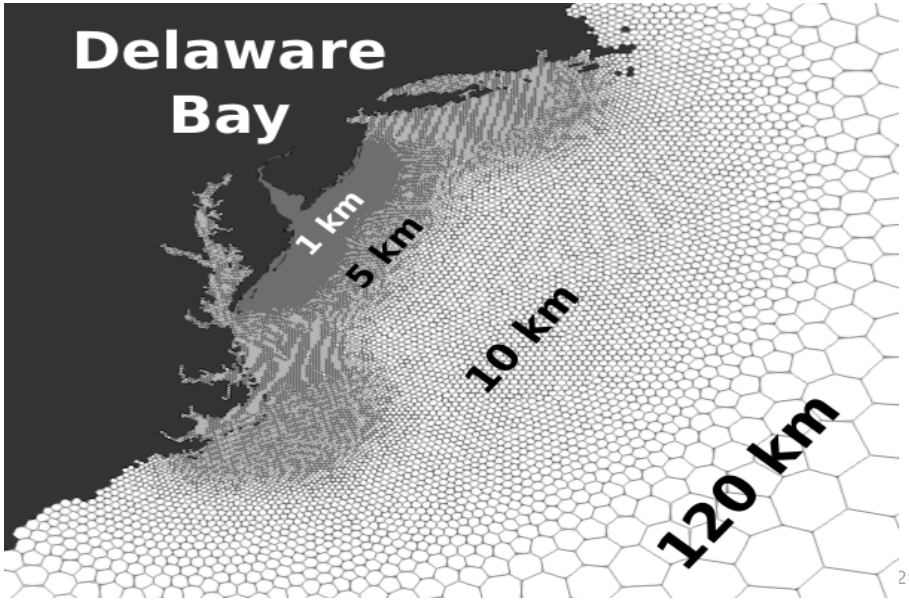
- LANL is actively developing GeoRad-Ionosphere, based on NRL's SAMI3.
- GeoRad-Ionosphere has an emerging nested grid capability designed to resolve D-Region with high-precision (sub-km).
- Plan to extend SAMI chemistry (7 ions) and incorporate advanced schemes.



Sensitivity of VLF signals to D-Region using FDTD

- GeoRad-FDTD is a full wave FDTD code that runs on an unstructured Voronoi tessellation (mostly hexagons and pentagons).
- Work is on-going to couple of variety of chemistry schemes to this code.



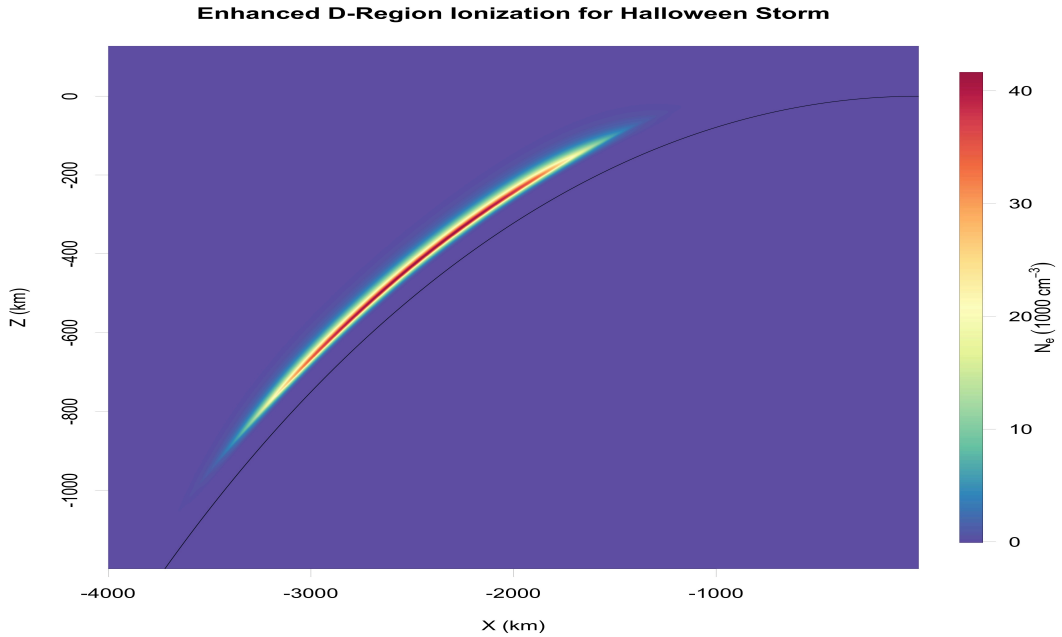


First Research Step: What is phenomenology of VLF propagation with Disturbed D-Region?

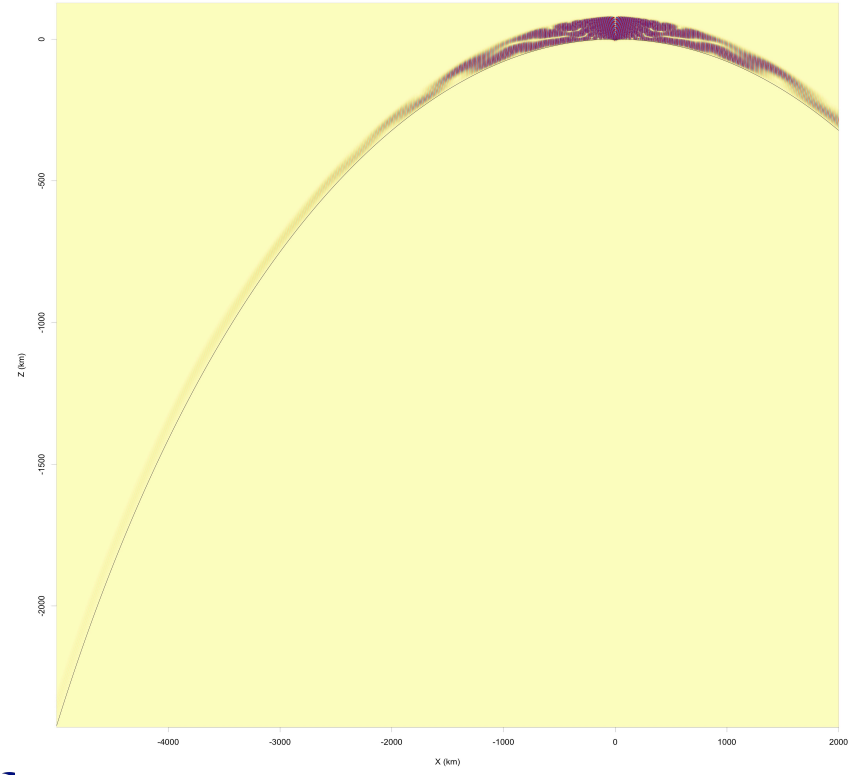
- GeoRad-MicroFade: Frequency-domain full wave solver in 2D.
- Physics and Numerics:
  - 6^{th} order Laplacian stencil in model domain and at boundaries (Higdon BCs)
  - High-performance framework for 100+ million cells using Mumps sparse matrix solve.
  - Full magnetic dispersion relation; present results are non-magnetic.
  - Coupled to D-Region chemistry perturbations from solar MeV protons.
- Relation to FDTD: many frequencies can be FFTed and compared.
- Initial results are of coupling of D-Region chemistry with Earth-Ionosphere wave-guide are surprising and need further investigation.
- Very interested in feedback from ICEAA/USRI participants on wave-guide effects.

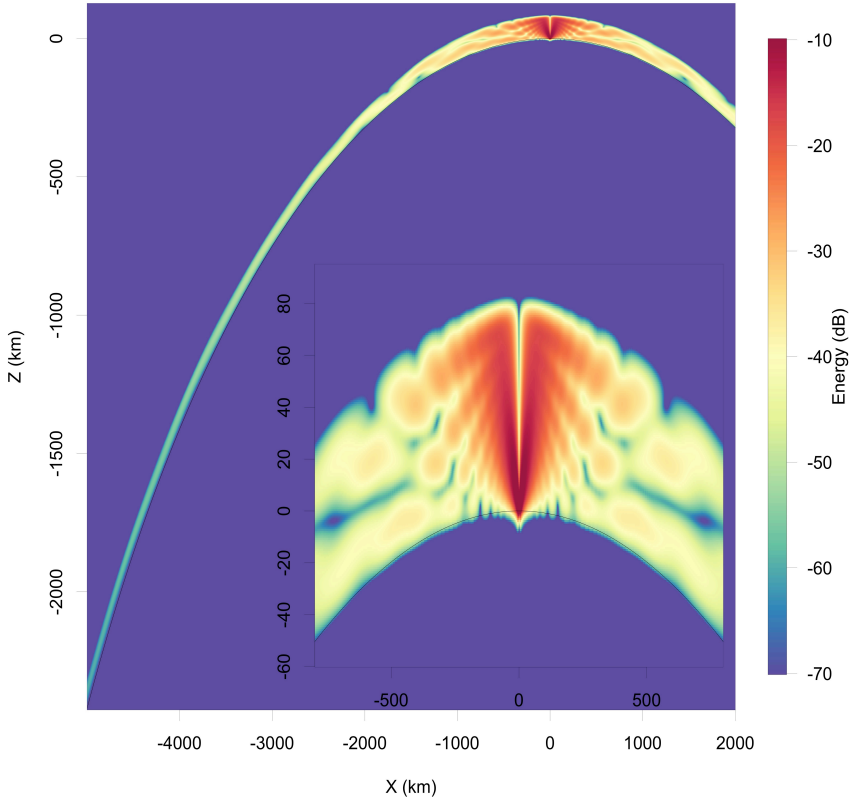
Model Set-Up

- Full wave VLF propagation with 20 kHz vertical E-field source simulated using GeoRad-MicroFade with 40 million cells in 2D and 700 m resolution.
- LANL chemistry model predicts enhanced D-Region ionization for the Halloween Storm, Oct, 2003.



VLF Signal Waveform & Energy





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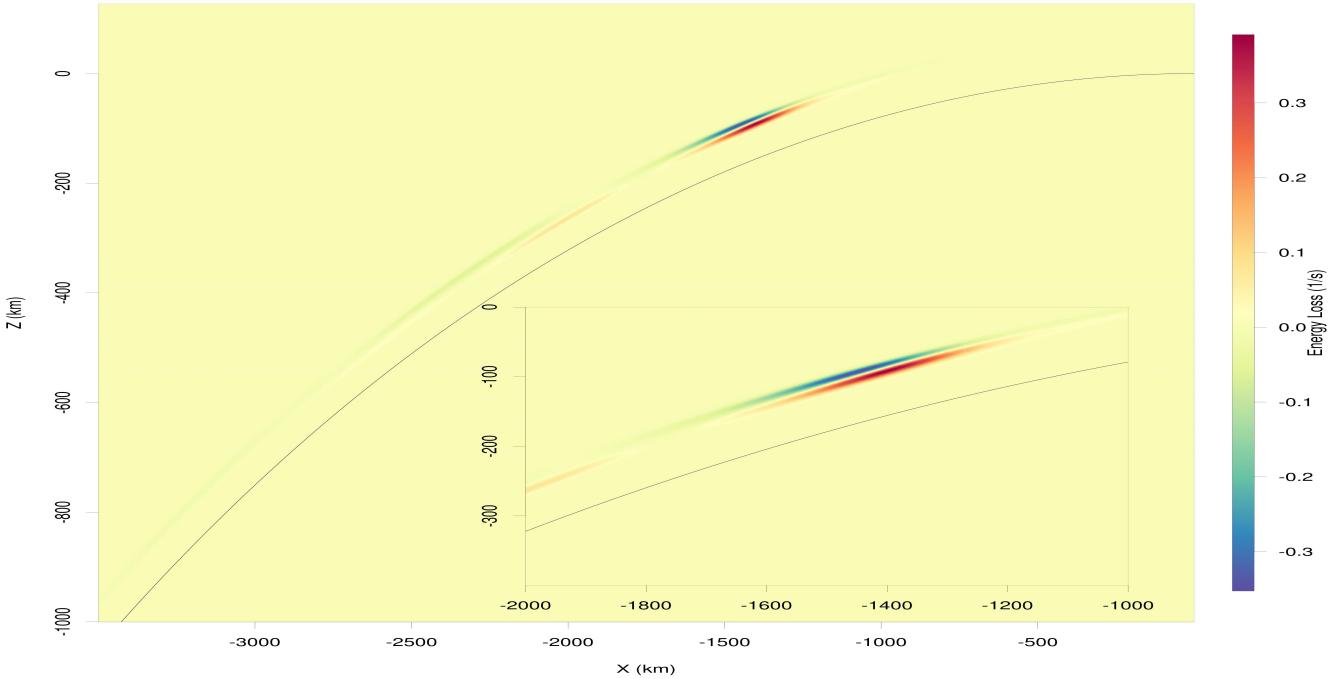
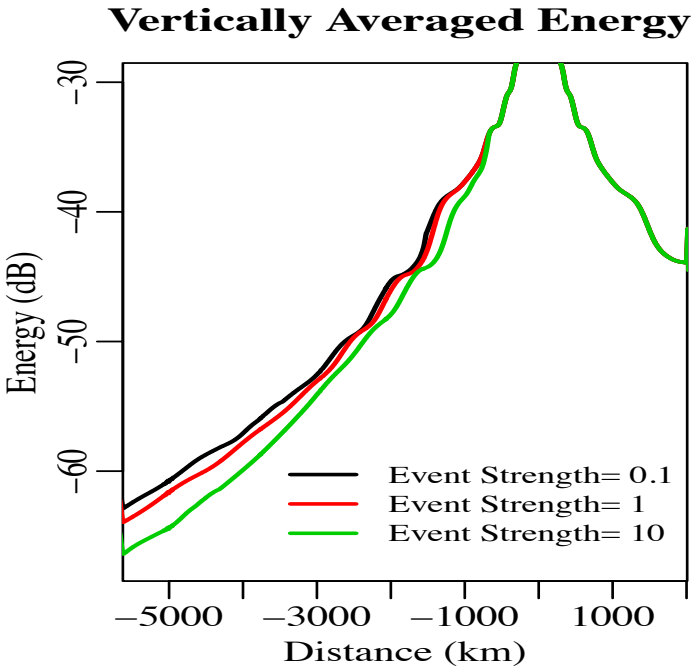
VLF Energy Loss: Wave-guide is compressed

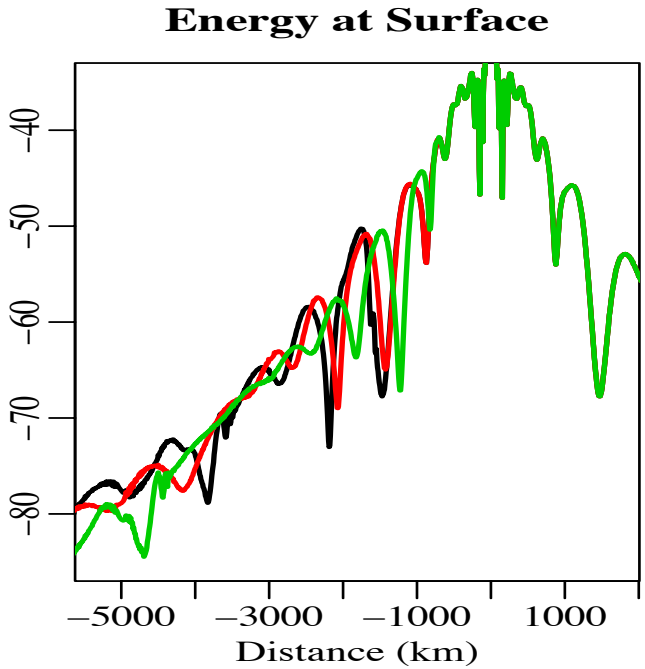


- Enhanced D-Region ionization compresses wave-guide.
- Attenuation shifts to lower altitudes.

Energy Analysis

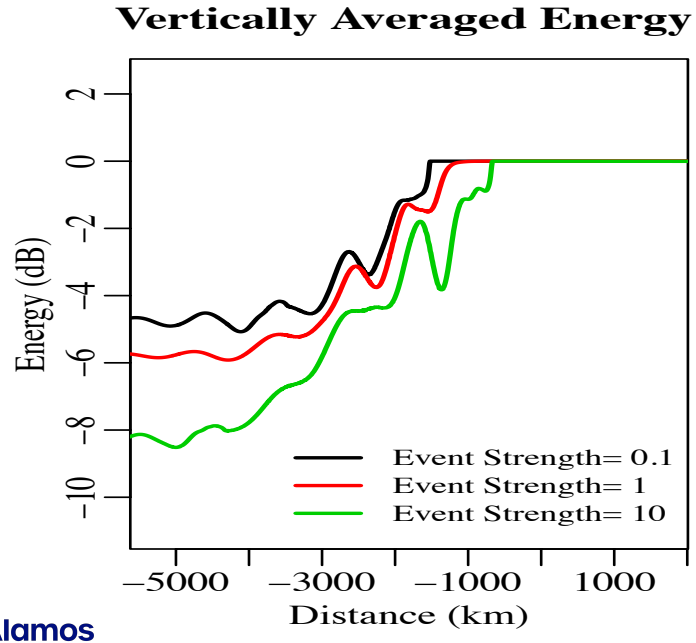
- Vertically-averaged energy shows expected attenuation with distance.
- Energy at surface exhibits strong wave-guide pattern.

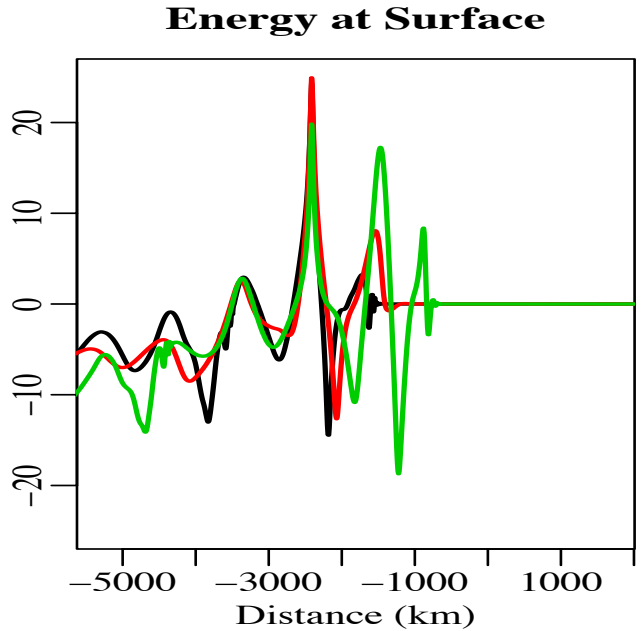




Normalized Energy Analysis

- Energy is normalized by quiescent/non-disturbed values.
- Very interesting patterns emerge at the surface.
- Adding VLF signal bandwidth, e.g. 20-21 kHz average, will smooth out a little, but pattern should remain.





Summary

- LANL is developing the GeoRad Tool Suite to predict D-Region disturbances and communication impacts.
- Our analysis of detailed D-Region chemistry schemes reveals large differences in the prediction of net electron detachment, and resulting communication impacts.
- GeoRad-MicroFade, an HPC frequency-domain full wave solver, is used to assess the sensitivity of VLF signals to D-Region disturbances in 2D.
- We have found strong wave-guide effects that need further modeling and investigation.
- Analytic models are sought that can predicted the wave-guide patterns that we observe.